Phase Noise Reduction of Laser Diode

T.C.Zhang
Institute of Opto-Electronics, Shanxi University, Taiyuan, Shanxi 030006, PRC

J.-Ph.Poizat, P.Grelu, J.-F.Roch, P.Grangier
Institut d'Optique, B.P.147, F91403 Orsay Cedex-France

F.Marin, A.Bramati, V.Jost, M.D.Levenson, and E.Giacobino
Laboratoire Kastler Brossel, Universite Pierre et Marie Curie, F75252 Paris Cedex 05-France

Abstract

Phase noise of single mode laser diodes, either free-running or using line narrowing technique at room temperature, namely injection-locking, has been investigated. It is shown that free-running diodes exhibit very large excess phase noise, typically more than 80 dB above shot-noise at 10 MHz, which can be significantly reduced by the above- mentionned technique.

PACS numbers: 42.50.Px, 42.50.Dv, 42.62.Fi

1 Introduction

Quantum intensity noise reduction of laser diode based on pump noise suppression has been extensively studied since 1984 [1]. Intensity squeezing of constant-current- driven laser diodes was observed for the first time by Machida et al in 1987 [2], and further improved to 8.3 dB in 1991 [3]. This last result was obtained at 66 K. In 1993, it was shown by Steel and his group[4] that line narrowing techniques (see [5] and references therein) greatly helped in the noise reduction. Intensity squeezing of 1.8 dB (2.0 dB corrected) at room temperature was obtained by injection-locking the laser [6] or by feedback from an external grating [4]. However, all the experiments realized so far were limited to measurement of intensity noise. How about the phase noise? In fact, in the early time in 1980's, Yamomoto et al [7] and Spano et al [8] studied the phase noise in laser diode, but they did not measure the phase noise with a reference to the standard quantum limit.

It is well known that in injection scheme the slave laser locks its frequency, and therefore its phase to the master laser. To our knowledge, the effect of injection locking on quantum phase-noise of laser diodes has not yet been reported experimentally. In reference [9], it is mentioned that injection-locking of a regularly pumped slave laser could lock the phase of the slave laser to the master laser, reducing thereby the excess phase-noise leading to a minimum uncertainty state(true squeezed state), if the master laser has a shot-noise- limited phase noise.

In this paper, we investigated the phase noise of laser diode, using injection-locking with a Ti:Sapphire laser. We have shown that the large excess phase noise of semiconductor lasers can be reduced by this technique.

2 Experimental Set-up and General Features

The laser diodes we have used are index-guided quantum well GaAlAs laser diodes (model SDL 5422-H1 and SDL 5411-G1), operating at 850 and 810 nm. The rear facet reflection coefficient is 95%, the front facet is AR coated with a reflection coefficient of about 4%. The laser diodes are temperature stabilized and carefully electromagnetically shielded.

The free-running laser diodes have a rather low threshold of 18 mA and a differential quantum efficiency (slope above threshold) of 66%. The operating current in the experiments described below is typically 5 to 7 times larger than the threshold current.

The injection-locking scheme is depicted in Fig.1. The master laser is a Ti:Sapphire laser which is frequency stabilized (linewidth of 500 kHz) and both intensity and phase are shot-noise limited. It is injected into the slave laser by means of an optical isolator. The master beam enters through the escape port of the polarizer placed after the Faraday rotator. Locking is observed on a rather broad power range[1] of the master laser, from 1 to 4 mW. The direction of the master laser must be carefully adjusted for optimum phase noise reduction.

3 Phase Noise Detection Scheme

The investigation of the phase noise of a laser beam requires a phase-to-amplitude converter, i.e. a device whose complex transmission T depends on the frequency ω. In this work, we use for this purpose the reflection off an empty detuned Fabry-Pérot cavity as shown in Fig.2. When the rear mirror is highly reflecting, this system has the advantage over a Mach-Zehnder interferometer that the mean field transmission $\mid T(\omega = 0) \mid$ does not depend on the cavity detuning and is always equal to unity. This makes shot-noise reference level independent of the analysed quadrature. Phase noise analysis is then carried out conveniently for frequencies in the range of the cavity bandwidth.

Explicit expressions of the quadrature rotation after reflection off a detuned Fabry-Pérot cavity are given in reference [10]. A simple way to understand this effect is to have in mind that in Fourier space, the quadrature component $X(\omega)$ can be written as

$$X(\omega) = (a(\omega) + a^{\dagger}(\omega))/\sqrt{2} = (a(\omega) + [a(-\omega)]^{\dagger})/\sqrt{2}.$$

The key point which yields a quadrature rotation is that the various frequency components at 0 (mean field), ω and $-\omega$ do not undergo the same phase shift when the laser is scanned across the resonance peak of the cavity. The quadrature rotation is zero in two cases : when the laser is tuned exactly on resonance, where the phase shifts for both frequency components $\pm\omega$ cancel out, and when it is tuned far outside the peak, where all frequency components undergo the same phase shift of 0 or π.

In our set-up the Fabry-Pérot cavity has a half-width at half-maximum (HWHM) of 8 MHz and a finesse of $\mathcal{F} = 125$. The rear mirror is highly reflecting, but its small leaks nevertheless allow us to monitor the intracavity intensity to adjust the mode matching. One of the mirrors is mounted on a piezo-electrical transducer, so that the length of the cavity can be scanned.

[1]It should be mentionned that only a small fraction (a few %) of this injected power is actually coupled to the lasing mode of the diode due to the imperfect mode overlap.

4 Experimental Results

We have measured the quadrature noise of a free-running and injection-locked laser diode. These results are presented in Fig.3. The phase noise (quadrature angle $\pi/2$ with respect to the mean field) is inferred from the experimental curves by fitting them with a simple model (see reference [10]). This model has a single adjustable parameter which is the excess phase noise.

This value has then to be corrected for various losses : propagation from the output of the laser to the detectors (3 dB), scattering losses inside the analyzing cavity (3 dB on resonance), imperfect mode-matching to the cavity (1 dB).

The phase noise inferred at the laser output for the free-running diode and the injection- locked scheme are respectively of 82 dB, and 46 dB above the shot-noise level.

Let us compare these experimental results with the prediction given by the Schawlow- Townes model [11]. Within this model, the phase noise normalized to the shot-noise level at a noise angular frequency $\omega = 2\pi f$ is

$$V_\Phi(\omega) = 1 + \frac{8DI_o}{\omega^2}(1+\alpha^2) = 1 + \frac{2\kappa^2(1+\alpha^2)}{\omega^2} \tag{1}$$

where I_o is the flow of photon outside of the laser (photons/sec), κ is the cavity decay rate for intensity, α is the line enhancement factor[12] (also called phase-amplitude coupling coefficient), and D is the Schawlow-Townes phase diffusion coefficient defined as:

$$D \doteq \frac{\kappa^2}{4I_o} \tag{2}$$

The first term is the contribution of the vacuum fluctuation (shot-noise) and the second term is due to the phase diffusion assuming a random walk of the phase in the laser.

Using the value of κ deduced from the experiment[2], one can calculate a theoretical estimation of the phase noise if the factor $(1+\alpha^2)$ is known. Conversely, by using the experimental value of the phase noise, one can deduce a value of $(1+\alpha^2) = 10$, which is in agreement with other measurements. However, the linewidth of the laser diode was also measured directly by sending the light through a Fabry-Pérot cavity with a linewidth (HWHM) of 2 MHz. We obtained $D(1+\alpha^2)/(2\pi) = 2$ MHz (HWHM linewidth). Using the value $I_o = 2.5 \times 10^{17}$ phot/sec corresponding to 60 mW laser output, the above model predicts $D(1+\alpha^2)/(2\pi) = \kappa^2(1+\alpha^2)/(8\pi I_o) = 50$ kHz, which is significantly smaller than the measured value. This discrepancy could be attributed to jitter of the laser frequency due to power supply noise and thermal fluctuations.

In the injection locking case, the phase noise reduction mechanism relies on the fact that the slave laser locks its phase to the one of the master laser [13]. The phase noise of this master laser is therefore of great importance. In this experiment we have used a frequency-stabilized Ti:Sapphire laser, which has a linewidth of 500 kHz and is both phase and intensity shot-noise limited at 10 MHz. We have observed a very significant phase noise reduction, from 82 dB to 46 dB for an injected power of 2 mW (see Fig.3(b)).

---

[2]The quantity $1/\kappa$ is the lifetime of the photon in the laser diode cavity, calculated from the measured free spectral range of $\Delta\lambda = 0.12$ nm, and from the transmission coefficient of the output mirrors ($R_1 = 95\%$ and $R_2 = 4\%$). This yields $\kappa = (c\Delta\lambda/\lambda^2)\ln(1/(R_1R_2)) = 1.8 \times 10^{11}\ \mathrm{s}^{-1}$.

Finally, let us emphasize that the quadrature noise detection scheme that we used is expected to work well only for a true single-mode laser. This is not the case for so-called "single mode" laser diode, for which weak longitudinal side-modes are very noisy and can play therefore an important role in the overall noise behaviour [14]. As long as the intensity noise power in the main mode is small with respect to the total phase noise power, which is generally the case in the results described above, these effects can be neglected. However, one has to be cautious in some cases. For instance, it can be noticed that the experimental trace of Fig.3(b) exhibits a slight asymmetry around its basis. This effect can be modelled simply, using an input covariance matrix such that the main axis of the noise ellipse is not exactly the phase axis (quadrature angle $\pi/2$) but is slightly tilted. In our experiments, this small rotation effect has been observed for the injection-locked laser, decreases as the driving current increases, and the dip on the right-hand side was always above shot-noise [15]. It is likely that a detailed analysis of this effect should include the contributions of the small modes, since intensity-phase correlations are essential in this process.

The intensity noise in this process was also measured and intensity squeezing was obtained and we have another paper to discuss these effects in details (See E.Giacobino's paper in this issue).

5 Conclusion

In this paper we have reported on a detailed experimental analysis of phase noise of commercial laser diodes at room temperature. We have studied the free-running diode and the injection-locking diode. The main result is that laser diodes exhibit a very large excess phase noise (up to 80 dB above shot-noise) and in the injection-locking scheme, the phase noise reduction mechanism involves the master laser, and using a shot-noise limited frequency stabilized Ti:Sapphire laser, we observed a reduction of the phase noise from 82 dB to 46 dB above shot-noise.

We believe that these results have important practical implications for spectroscopy and quantum optics experiments involving laser diodes. This results have also demonstrated that there is still a long way to realize the squeezed minimum uncertainty states with laser diodes.

6 Acknowledgments

This research was carried out in the frameworks of the ESPRIT Basic Research Project 6934 QUINTEC, and of the HCM network "Non-Classical Light" (ERB CHRX CT93 0114). Two of us had fellowships : TCZ was supported by a Programme International de Coopération scientifique (PICS) sponsored by the CNRS. and AB was supported by the HCM program from the European Community (ERB CHBG CT93 0437).

References

1. Yu.M. Golubev, I.V. Sokolov, Zh. Eksp. Teor. Phys, 87, 804, (1984) (Sov. Phys. JETP, 60, 234 (1984)).
2. S. Machida, Y. Yamamoto, and Y Itaya, Phys. Rev. Lett., 58, 1000 (1987);
3. W.H. Richardson, S. Machida, and Y. Yamamoto, Phys. Rev. Lett., 66, 2867 (1991).
4. M.J. Freeman, H. Wang, D.G. Steel, R. Craig, and D.R. Scifres, Opt. Lett., 18, 2141 (1993).

5. C.E. Wieman and L. Hollberg, Rev. Sci. Instrum., 62, 1 (1991).
6. H. Wang, M.J. Freeman, and D.G. Steel,Phys. Rev. Lett., 71, 3951 (1993).
7. S.Saito, Y.Yamamoto, Electronics Letters, 17, 327 (1981).
8. B.Daino, P.Spano, M.Tamburrini and S.Piazzolla, IEEE, Journal of Quantum Electronics,QE-19, 266 (1983).
9. H.M.Wiseman and G.J.Milburn, Phys.Rev.Lett., 70, 548 (1993).
10. T.C.Zhang, J-Ph.Poizat, P.Grelu, J-F.Roch, P.Grangier, F.Marin, A.Bramati, V.Jost, M.D.Levenson and E.Giacobino, Quantum and Semiclassical Optics, 7, (1995)to be published.
11. A.L. Schawlow and C.H. Townes, Phys. Rev., 112,1940 (1958).
12. C.H. Henry, IEEE J. Quantum Electron., 18, 259 (1982).
13. P. Spano, S. Piazzolla, and M. Tamburrini,Opt. Lett.,10, 556 (1985); IEEE J. Quantum Electronics, 22, 427 (1986).
14. F. Marin, A. Bramati, E. Giacobino, T.-C. Zhang, J.-Ph. Poizat, J.-F. Roch, and P. Grangier, submitted to Phys. Rev. Lett.
15. A. Karlsson and G. Björk, Phys. Rev. A, 44, 7669 (1991).

FIGURES

Fig.1. Injection-locking scheme. The Faraday rotator rotates the linear polarization by 45°. PBS is a polarizing beam splitter. The master laser is a frequency stabilized Ti:Sapph laser.

Fig.2. Phase noise detection set-up. Great care has been given in order to avoid any feedback from the analysing cavity to the laser, and optical isolation (OI) of about 80 dB has been used. The rear mirror is a high reflector and its position is controlled by a piezo electrical transducer (PZT).

Fig.3. Raw noise power at 10 MHz as the laser diode is scanned across the peak of the analysing Fabry-Perot cavity. (a) for the free-running laser diode, (b) for the Ti:Sapph injection-locked laser diode. The laser diode driving current is 80 mA. The reference level 0 dB is the shot-noise level. The resolution bandwidth is 1 MHz with a video filter of 10 kHz. On each graph the thin line is the best fit using the theoritical expression. The small peaks on the sides are due to an imperfect mode-matching.

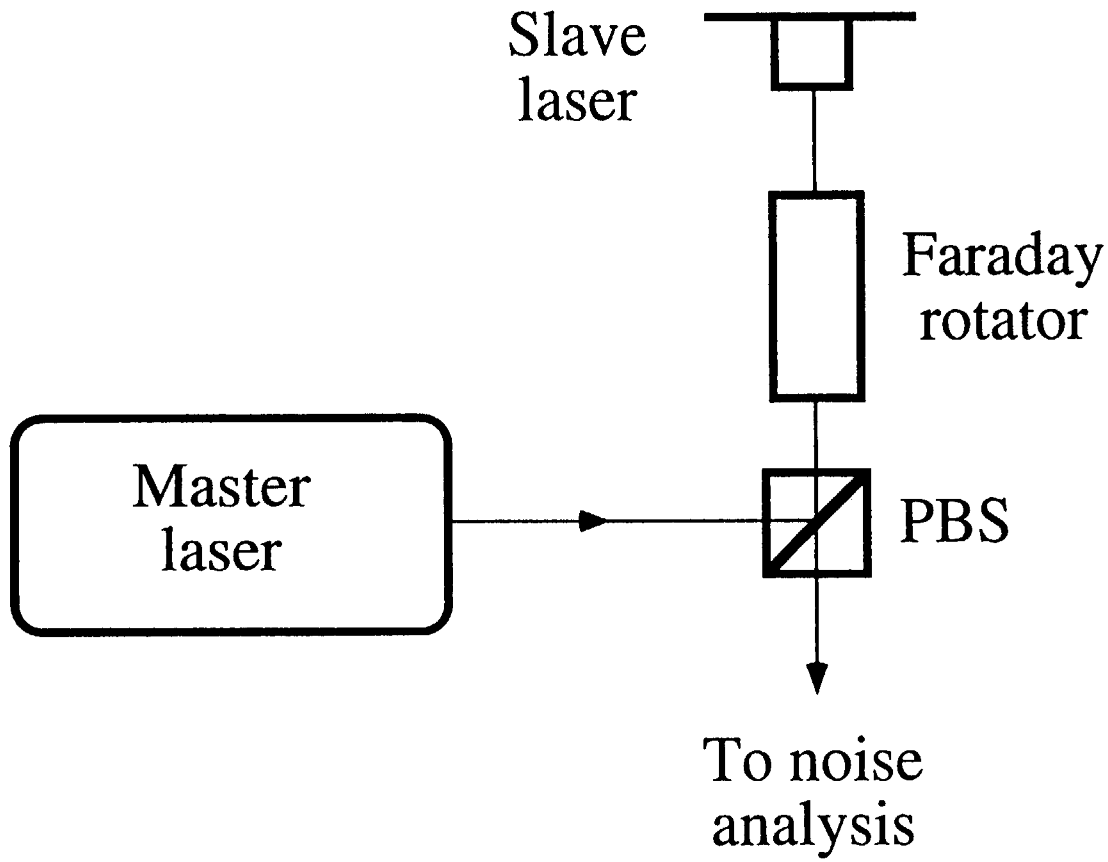
Slave
laser
Faraday
rotator
Master
laser
PBS
To noise
analysis

Fig.1

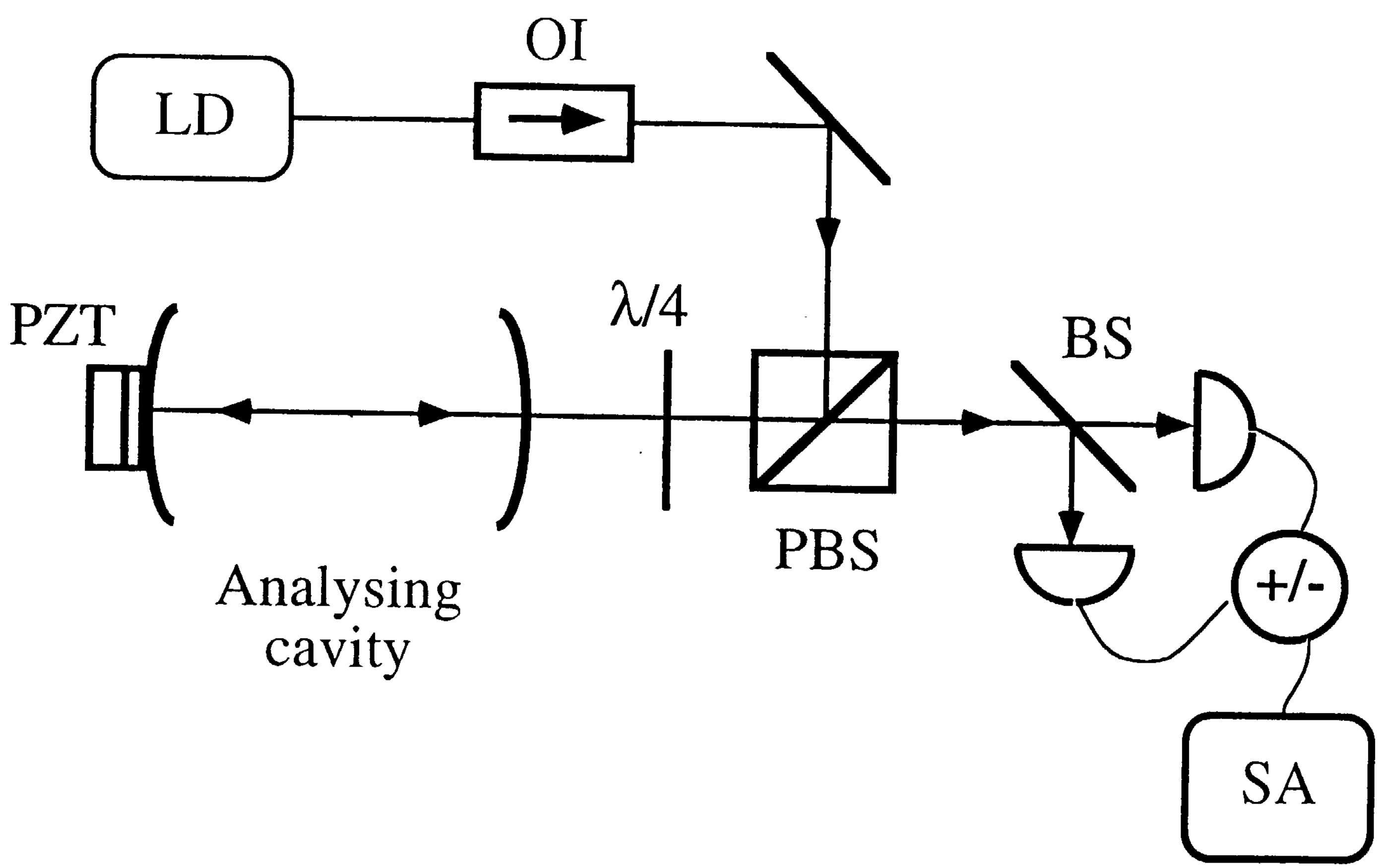

Fig.2

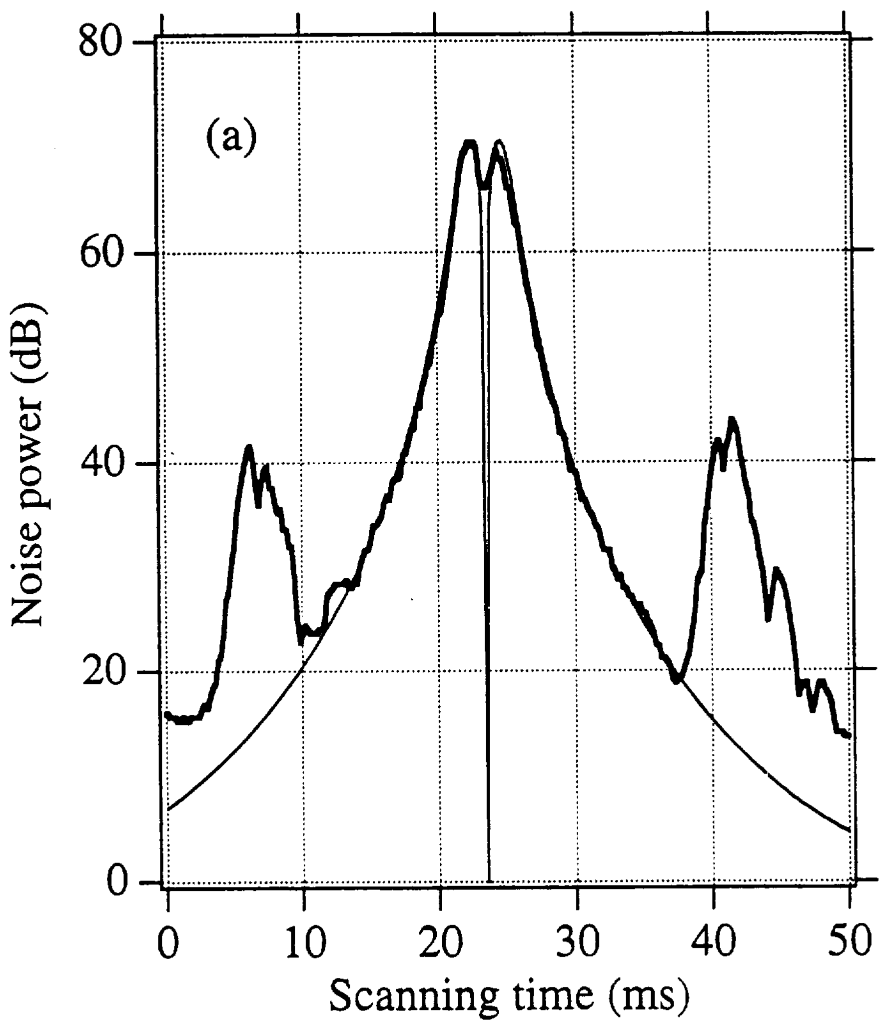

Fig.3(a)

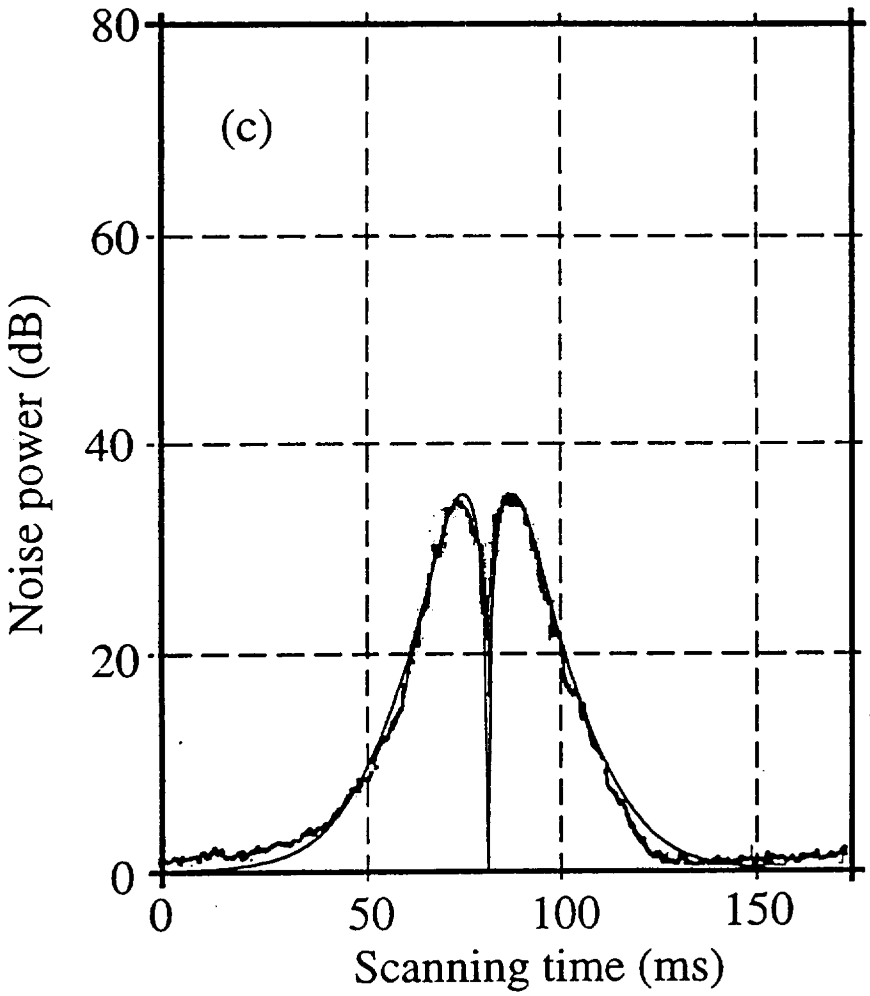

Fig.3(b)